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by Ulysse J. Blanchard

Langley Research Center

Langley Station, Hampton, Va.

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SUMMARY

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In order to determine the suitability of landing systems for lunar spacecraft, it is necessary to study the landing-gear structural loads, vehicle loads, motions, and stability at lunar gravity and at full size. There is need of a practical and economical technique for conducting full-scale earth tests which would augment small-scale model and analytical investigations. An investigation of a 1/6-scale dynamic model has been made to develop and evaluate a technique for conducting full-scale landing-impact tests at simulated lunar gravity. Results of the simulator tests at lunar gravity show good correlation with results obtained during free-body earth-gravity landing tests using the 1/6-scale dynamic model. Impact accelerations, time histories, and gear strokes obtained during hard-surface landings using both techniques are in good agreement. Behavior and overturn characteristics compare favorably. These tests indicate that the simulator technique could be used to conduct a full-scale two-dimensional investigation of a lunar spacecraft landing-gear arrangement over a range of spacecraft landing speeds, flight-path angles, pitch attitudes, and gear orientations during landings on selected surfaces. A motion-picture film supplement (L-856) is available to illustrate the results of these tests. A request card and a description of the film are provided at the end of this paper.

Author

INTRODUCTION

The landing gear for a manned lunar spacecraft as presently envisioned represents a new concept having structural design problems which involve geometry, mass, impact attenuation, and environmental conditions uncommon to present-day earth-landing systems. Final optimization and proof of the landing-gear structure and demonstration of the vehicle stability can best be achieved by subjecting the full-scale landing-gear configuration to the landing-impact dynamics and conditions expected during lunar landing. In order to maintain dynamic similarity during impact testing of the full-scale vehicle, it is necessary that the lunar gravitational field be simulated.

Several methods can be used to simulate the lunar gravitational force (1/6-earth gravity) for prototype studies on earth. These include monitored lift cables or gimbaled lift engines which counteract 5/6 of the force due to gravity (weight) at the center of gravity of the vehicle. Cable-lift systems require complex balance and servomechanisms to maintain the proper gravity effect during the entire impact. The gimbaled engine presents interference and geometry problems. Existing systems of this type are primarily intended for research and pilot training during the landing-approach and hovering phase of the lunar landing for which required response rates are lower than would be necessary during actual landing impact. The elevator technique described in reference 1 obtains a relative acceleration of 1/6 g between the impact platform and the free-body vehicle (under 1 g influence) during landing by means of a counterweight or inertia wheel which drops the platform at 5/6 earth gravity. However, the size and complexity required to obtain adequate impact time with this simulator might make the cost high.

An inclined-plane technique, previously employed for man's self-locomotion tests at lunar gravity (ref. 2) has been studied at the NASA Langley Research Center to develop an adequate, economical, and practical lunar-gravity simulator that would be particularly applicable to landing-impact investigations of full-scale lunar-landing spacecraft. The technique is restricted to two-dimensional studies. It could also be utilized for simulation of landings on other planets and satellites with gravity lower than that of earth. The results of proof tests of this system conducted with a 1/6-scale model are presented herein and are compared with free-body tests under earth-gravity influence.

SYMBOLS

The units used for the physical quantities defined in this paper are given both in the U.S. Customary units and in the International System of Units (SI). Factors relating the two systems are given in reference 3.

A	area, ft^2 or m^2
a	acceleration, ft/sec^2 or m/s^2
F	force, lb or newtons (N)
g	gravity
I	moment of inertia, slug-ft^2 or kg-m^2
l	length, ft or m
m	mass, slug or kg
t	time, sec
V	velocity, ft/sec or m/s

V_H	horizontal velocity, ft/sec or m/s
V_R	resultant velocity, ft/sec or m/s
V_V	vertical velocity, ft/sec or m/s
X,Y,Z	coordinates of body-axis system
α	angular acceleration, radians/sec^2
β	gravitational ratio, g_{earth}/g_{lunar}
γ	flight-path angle, deg
λ	geometric model scale
μ	coefficient of friction
σ	stress, lb/in.^{2} or N/m^2
ω	angular velocity, radians/sec

DESCRIPTION OF EQUIPMENT AND TESTS

The geometry and principle for obtaining the equivalent of lunar gravity are shown in figure 1. The desired reduced gravity was obtained by cable suspension and by inclining the test vehicle and the landing surface at the required angle relative to the vertical earth-gravity vector. The inclination was established by displacing the landing surface from directly beneath the point at which the suspension cable was attached to the support structure. The vehicle was essentially free to translate in a single two-dimensional plane normal to the landing surface (fig. 1) and to rotate about an axis normal to this plane. All other motions were constrained.

Model

The general arrangement of the 1/6-scale model used for both the simulator (lunar-gravity) and the free-body (earth-gravity) tests is shown in figure 2. Full-scale and model scaling relationships applicable to these tests are given in table I. Pertinent model and full-scale dimensions are given in table II.

The model was constructed of a solid hardwood and balsa core containing appropriate cavities for instrumentation and ballast. It was the same model used for a previous investigation described in reference 4. The landing gear had a quadruped configuration; each leg consisted of three struts mounted to form an inverted tripod as shown in figure 3. The shock strut telescoped during impact and the lower V-strut was a hinged unit, which served to guide and stabilize the tripod. During impact the telescoping shock strut yielded a metal energy strap in tension for impact attenuation. The energy straps were made of low-carbon nickel, a highly ductile metal which stores very little energy during yield, thus minimizing rebound. The shock-absorber element used on the model had desirable characteristics for the lunar-landing mission. These characteristics could also be obtained by using other systems such as crushable materials, frangible tubes, or properly designed oleo systems.

Scaling Laws

The scale relationships pertinent to the 1/6-scale model test on earth (table I) were based on the following criteria: For geometric scaling the characteristic length was varied as the scale factor λ. The same yield-strap material was assumed for the model and the full-scale configurations; hence, the stress relationship would be 1 to 1, so that exact structural scaling of shock-absorber forces was provided. In the case of the earth-gravity model (earth gravity acting) the gravitational ratio β is dictated by the fact that the force due to the earth's gravity is 6 times that of the moon; thus, accelerations experienced by the model were 6 times that which would occur on the moon. With these three relationships fixed, other pertinent scale relationships follow from laws of physics for a dynamically scaled model.

In the case of the lunar-gravity model tests (lunar gravitational force simulated) it was convenient to use the existing earth-gravity model without altering its mass and inertia; therefore, the landing-gear shock-absorber force was necessarily scaled by λ^3 instead of λ^2 (the force of the lunar-gravity model is 1/6 that of earth-gravity model force). As a result the cross-sectional area of the energy straps was scaled by λ^3, and mass and inertia ratios of λ^3 and λ^5, respectively, were a requisite. The latter two factors were equivalent to those of the earth-gravity model.

Apparatus and Procedure

The investigation was conducted by launching the model as a free body with earth gravity acting and also as a tethered body under simulated lunar-gravity conditions. The present free-body tests were conducted by means of a pendulum apparatus illustrated in figure 4 which was similar to that described in reference 4. The lunar-gravity tests were conducted by landing the modified model, shown in figure 5, with a simple-pendulum apparatus (fig. 6); a pendulum-catapult system (figs. 7 and 8); and an alternate pendulum-catapult technique (fig. 9). In general the simulators consisted of an inclined-plane landing surface and a support cable which in combination maintained the desired gravity reaction on the test vehicle during landing, and a launching device used to obtain the desired impact speed and attitude relative to the landing surface. On all simulators the support-cable length was about 20 feet (6.1 m) and the cable angle relative to the local earth vertical was nominally $9\frac{1}{2}^{\circ}$ (1/6 g reaction) at impact. Maximum displacement of the center of gravity of the model normal to the landing surface due to touchdown attitude, pitch motions, or landing-gear stroke was about 1/3 of a foot (0.1 m). This displacement produced small changes in cable angle during landing and a subsequent gravity-ratio change of approximately 0.02 or less when determined by the method presented in reference 2.

Simple-pendulum simulator.- The simple-pendulum apparatus illustrated in figure 6 had a fixed pivot point at the upper end of the support cable. The support cable was also used as a pendulum device for obtaining initial landing conditions. The model was retracted from the landing surface to a release point from which it was allowed to swing in an arc to the landing surface. During the swing the model impacted at a point along the flight path then completed the landing slideout along a shallow curved path on the landing surface. The desired landing speed along the flight path was obtained from gravitational force by adjusting vertical displacement of the pendulum between release and impact. Landing pitch attitude (about the Y-axis shown in fig. 6) was set by adjustment of the retraction and release linkages so that the model was released at the desired attitude and maintained this attitude as a result of the low torsion force in the single support cable. Roll and yaw attitude (X- and Z-axis, respectively) were constrained by the geometry and attachment of the support cable.

Pendulum-catapult simulator.- The pendulum-catapult apparatus illustrated in figure 7, includes an overhead track and trolley which allowed the suspension system to translate and slave to the model center-of-gravity motions parallel to the landing surface - that is, along the horizontal velocity vector. The trolley had very low rolling friction and the mass ratio of the trolley and suspension cable to the model was 1 to 40. Horizontal velocity V_H relative to the landing surface was obtained by a parallel catapult track and the stroke of a counterweight for acceleration to launch speed. The counterweight was arrested at the moment the model dropped off the end of the catapult track. The desired vertical velocity V_V was obtained by adjusting the pendulum displacement to the landing surface. The combination of horizontal velocity at catapult track separation and vertical velocity at impact determined the flight-path trajectory at model touchdown. Pitch attitude was obtained by adjustment of the launching cables and the catapult-track bearing of the model on an arc about the center of gravity of the model (figs. 5 and 8). Roll and yaw attitude were constrained.

An alternate pendulum-catapult method shown in figure 9 was very briefly evaluated. This system replaced the counterweight catapult with a double-cable pendulum for catapulting the model at the desired horizontal speed. The free translating overhead trolley and suspension cable were retained. At dead center and maximum horizontal speed (relative to the landing surface) the vehicle was released by the double-cable pendulum and allowed to fall toward the landing surface accelerating to the desired vertical speed.

Landing surface.- The landing surface used for both earth-gravity and simulated lunar-gravity tests was a frame-supported platform consisting of planking overlaid with a sheet of fir plywood. For lunar-gravity tests the platform was inclined at an angle of $9\frac{1}{2}^{\circ}$ from vertical (figs. 6 and 7). The sliding coefficient of friction μ range of the model pads was from 0.4 to 0.5 on plywood. A coefficient of friction from 0.1 to 0.2 was obtained by installing a sheet of steel over the platform and coating it with light oil. Also, a friction coefficient from 0.6 to 0.7 was obtained by applying a coarse grit material to the pad surfaces and landing on plywood. A downhill slope of approximately 9° was simulated by landing with the trailing landing-gear pads contacting an elevated ledge or shelf mounted on the surface and representing a full-scale height of 2 feet (0.6 m).

Instrumentation and measurements.- Landing impact accelerations were measured by strain-gage accelerometers rigidly mounted in the model. Normal acceleration of the center of gravity was measured with a 20g accelerometer. Longitudinal acceleration was measured with a 15g accelerometer mounted above the normal accelerometer. Angular acceleration was measured with a pair of matched 50g accelerometers. The accelerometers were damped to 65 percent of critical damping. The response of the recording galvanometers was flat to 120 cycles per second for all circuits. A 20-kcps amplifier was used to adjust (amplify or attenuate) recording sensitivity by a factor of about 6 when shifting between the earth-gravity and lunar-gravity tests. Total gear stroke was obtained by measuring linear elongation of the energy straps after each landing. Impact and slideout motions were visually observed and were also recorded by motion-picture cameras.

Test parameters.- The orientation of vehicle axes, accelerations, attitudes, speeds, and flight-path angle during landings is shown in figure 10. Landings were made at touchdown pitch attitudes of -15°, 0°, and 15°. All landings were made with two gear pads forward and at a roll attitude of 0°. Both roll and yaw attitudes were constrained. Vertical landing speed was varied from 5 to 15 feet per second (1.5 to 4.6 m/s) and horizontal speed was varied from 0 to 10 feet per second (0 to 3.0 m/s). Most of the landings were made at a vertical and horizontal speed of 10 feet per second or 3.0 m/s (45° flight-path angle) while pitch attitude and surface characteristics, friction and topography, were varied. These parameters were investigated with the free-body earth-gravity and the simulated lunar-gravity test techniques. The landings were made at a model mass corresponding to a full-scale lunar weight (force due to gravity) of 1,440 pounds (6.41 kN) or an earth weight of 8,640 pounds (38.4 kN).

RESULTS AND DISCUSSION

All data presented have been converted to full-scale lunar values in terms of earth gravity by use of the scale relations given in table I. The data presented in figures 11 to 15 compare impact loads obtained during the present free-body landing tests and simulator tests using the pendulum-catapult apparatus (figs. 7 and 8). The data presented in figure 16 compare results obtained during simulator tests using two launch techniques. In figure 17 free-body stability characteristics are compared with characteristics obtained by means of the two simulator launch techniques.

Comparison of Landing-Impact Loads

Maximum accelerations experienced during landings at a full-scale vertical and horizontal speed of 10 ft/sec (3.0 m/s) on a flat hard surface are shown in figure 11 for various touchdown pitch attitudes and ranges of surface-pad coefficients of friction. The plots compare results of landing tests made with the free-body earth-gravity model and the tethered lunar-gravity model. The trends are similar and the impact accelerations are generally in good agreement. As the nominal value of coefficient of friction was increased (figs. 11(b) and 11(c)), some disagreement was noted during landings at a pitch attitude of -15°. At this particular landing attitude differences in longitudinal acceleration, due to variations in pad-surface friction forces during landing, could cause large differences in angular and normal acceleration because of the orientation of the impact resultant force relative to the vehicle center of gravity. This phenomenon also affects the overturn characteristics as shown by the solid symbols in figure 11(c). During landings on the ledge simulating a slope of approximately 9° good agreement was obtained between the earth-gravity and lunar-gravity tests as shown in figure 12.

Impact acceleration time-history comparisons of landings at three touchdown pitch attitudes are shown in figure 13 for the two test techniques, earth gravity and lunar gravity. These faired acceleration traces of oscillograph records were obtained during the landings on the lubricated steel surface with a coefficient of friction from 0.1 to 0.2. Generally good correlation exists for the impulse characteristics and times of the two test techniques. Similar results were obtained for the other friction values tested.

Comparison of Landing Behavior

Landing-gear stroke.- The maximum or total strokes of the forward and rear landing-gear legs during impact are compared in figure 14 for the three landing surfaces tested. The overall correlation for these data is good. As in the case of impact accelerations, stroke of the forward legs at an attitude of -15° was significantly affected by pad friction forces during landings at high nominal values of coefficient of friction (fig. 14(c)).

Figure 15 is a plot of the overall strokes of the upper and lower legs (see sketch in fig. 15) during landing impacts using the lunar-gravity technique. The purpose here is to indicate the effect of the inherent roll velocity (about the X-axis) imparted to the vehicle during the pendulum swing on the support cable. In general the lower legs stroked slightly more than the upper legs but this does not appear to be a serious condition for the present configuration. Larger landing-gear spans would exaggerate this condition but should not seriously degrade the usefulness of the test technique.

Landing stability.- During the investigation at lunar gravity the desired landing conditions were obtained by launching the model as part of a simple pendulum (fig. 6) and also a combination pendulum and counterweight catapult system (fig. 7). Impact accelerations experienced with both launch methods are shown in figure 16 and are practically identical as expected for the constant-force shock absorber employed on the vehicle. However, the behavior and motions were different for some test conditions as indicated in figure 17, which shows the overturn characteristics during tests at lunar gravity using the two launch methods as compared with the characteristics during tests at earth gravity (free body). Pitch attitude is plotted against horizontal speed at touchdown for a constant vertical speed of 10 ft/sec (3.0 m/s). The simple-pendulum launch method resulted in an increased tendency of the vehicle to overturn, particularly at pitch attitudes of $\pm 15^{\circ}$, whereas the correlation between the pendulum-catapult technique and the free-body landings is better. The left-hand sketch in figure 6 shows that at impact during landings having horizontal speed the suspension cable of the simple-pendulum apparatus is initially at some angle off vertical in a plane parallel to the landing surface. Gravity and this cable geometry generate a force on the vehicle in the direction of horizontal velocity which in turn induces an additional pitching moment about the pads. At high pad-friction values where the resultant impact-force vector is near the center of gravity of the vehicle the cable-induced force could be of significance with respect to the motions and stability. In contrast, the pendulum-catapult technique basically accelerates the entire suspension system up to the desired horizontal landing speed and essentially maintains an overhead position of the cable and pivot point relative to the test vehicle during the landing impact and slideout.

By using the double-cable pendulum (fig. 9) in lieu of the counterweight method for obtaining horizontal velocity it appears that some simplification of the pendulum-catapult technique could result for full-scale application. Motion pictures of a limited number of model landings indicate that such a system could be used to obtain desired initial landing conditions. The approximate preset launch attitude of the model and the measured touchdown attitude during three landings with the two catapult methods compare as follows:

Approximate launch attitude, deg	15	0	-15
Touchdown pitch attitude:			
Counterweight method, deg	$14\frac{1}{2}$	$-1\frac{1}{2}$	$-14\frac{1}{2}$
Double-cable pendulum method, deg . .	15	$-1\frac{1}{2}$	$-16\frac{1}{2}$

The attitudes at touchdown were within $\pm 1\frac{1}{2}^{\circ}$ which was considered acceptable. Since only the launch technique is different, similarity of load and stability characteristics during landing impact and slideout could be expected for equivalent landing conditions.

Full-Scale Application

The subject test technique is suggested for full-scale evaluation of the structural integrity and characteristics of a lunar-landing-gear system under dynamic loads resulting from landings at various touchdown conditions in a simulated lunar-gravity field. Simultaneous operation of all the prototype landing-gear components during impact could be studied. Motions and behavior predicted by small-model tests and analytical studies could be evaluated and verified. Extensive full-scale stability investigations may not be required since small-model techniques, once verified by the full-scale technique, would be much more economical and practical. The planar landing parameters that could be investigated include pitch attitude, pitch motion, gear orientation, vertical and horizontal velocities, surface friction variations, simulated obstructions, and hard or crushable homogeneous surface materials.

An adequate test vehicle would consist of a truss-frame or boiler-plate representation of the prototype mass and inertia characteristics to which would be attached the landing-gear structure. The test frame could be designed to accommodate gear configuration changes. Part or all the actual prototype structure in addition to the landing gear could be incorporated if desirable. Although results and emphasis of the subject study are directed toward lunar gravity and a lunar-landing vehicle, the technique is applicable for other planetary landings at reduced gravity.

Approximate overall dimensions necessary for a full-scale test facility adequate for the vehicle of the present investigation would be as follows:

	ft	m
Overhead trolley track length	150 to 200	46 to 61
Height of track above ground level . . .	150 to 200	46 to 61
Length of landing surface	100 to 150	30 to 46
Width of landing surface	About 40	12

CONCLUDING REMARKS

A 1/6-scale dynamic-model investigation has been made in order to develop and evaluate a technique for conducting full-scale landing-impact tests under the influence of lunar gravity. Results of the model tests at lunar gravity show good correlation with results obtained during free-body earth-gravity landing tests. Impact acceleration, time histories, and gear strokes experienced during hard-surface landings are in good agreement. Behavior and overturn stability characteristics compare favorably.

This investigation indicates that an inclined-plane technique utilizing simple and inexpensive cable suspension and launching equipment would be a practical method for conducting a full-scale planar investigation of a lunar spacecraft landing-gear arrangement. A range of spacecraft landing speeds, flight-path angles, pitch attitudes, and gear orientations could be studied during landings on selected surface features.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 9, 1964.

REFERENCES

1. Carden, Huey D.; Herr, Robert W.; and Brooks, George W.: Technique for the Simulation of Lunar and Planetary Gravitational Fields Including Pilot Model Studies. NASA TN D-2415, 1964.

2. Hewes, Donald E.; and Spady, Amos A., Jr.: Evaluation of a Gravity-Simulation Technique for Studies of Man's Self-Locomotion in Lunar Environment. NASA TN D-2176, 1964.

3. Mechtly, E. A.: The International System of Units - Physical Constants and Conversion Factors. NASA SP-7012, 1964.

4. Blanchard, Ulysse J.: Characteristics of a Lunar Landing Configuration Having Various Multiple-Leg Landing-Gear Arrangements. NASA TN D-2027, 1964.

TABLE I.- SCALE RELATIONSHIPS FOR 1/6-SCALE EARTH MODELS OF LUNAR-LANDING VEHICLE

λ = Geometric model scale, 1/6

β = Gravitational ratio, g_{earth}/g_{lunar}

Quantity	Lunar prototype	Earth-gravity model (β = 6)		Lunar-gravity model (β = 1)	
		Scale factor	Model scale	Scale factor	Model scale
[1]Length	l	λ	λl	λ	λl
[1]Stress (energy strap)	σ	1	σ	1	σ
[1]Acceleration	a	β	6a	1	a
Area (energy strap)	A	λ^2	$\lambda^2 A$	λ^3	$\lambda^3 A$
[2]Force	σA, ma	λ^2	$\lambda^2 F$	λ^3	$\lambda^3 F$
Mass	F/a	λ^2/β	$\lambda^3 m$	λ^3	$\lambda^3 m$
Velocity	$\sqrt{al}$	$\sqrt{\beta\lambda}$	V	$\sqrt{\lambda}$	$\sqrt{\lambda}\ V$
Time	V/a	$\sqrt{\lambda/\beta}$	λt	$\sqrt{\lambda}$	$\sqrt{\lambda}\ t$
Inertia	ml^2	λ^4/β	$\lambda^5 I$	λ^5	$\lambda^5 I$
Angular velocity	1/t	$\sqrt{\beta/\lambda}$	$\sqrt{1/\lambda^2}\ \omega$	$\sqrt{1/\lambda}$	$\sqrt{1/\lambda}\ \omega$
Angular acceleration	$1/t^2$	β/λ	$1/\lambda^2\ \alpha$	$1/\lambda$	$1/\lambda\ \alpha$

[1]Scale factor assumed.

[2]Lunar-gravity model shock-absorber force scaled by λ^3 which required that energy strap cross-sectional area be scaled by λ^3, mass by λ^3, and inertia by λ^5.

TABLE II.- PERTINENT DIMENSIONS OF LUNAR VEHICLE

	1/6 scale				Full scale	
	Earth gravity		Lunar gravity			
General:						
Mass	1.24 slugs	18.1 kg	1.24 slugs	18.1 kg	268 slugs	3910 kg
Gross weight (force due to gravity)	40.0 lb	178 N	6.7 lb	29.6 N	1440 lb	641 N
Moment of inertia (approximate):						
Roll	0.7 slug-ft^2	0.9 kg-m^2	0.7 slug-ft^2	0.9 kg-m^2	5443 slug-ft^2	7380 kg-m^2
Pitch	0.7 slug-ft^2	0.9 kg-m^2	0.7 slug-ft^2	0.9 kg-m^2	5443 slug-ft^2	7380 kg-m^2
Yaw	0.6 slug-ft^2	0.8 kg-m^2	0.6 slug-ft^2	0.8 kg-m^2	4666 slug-ft^2	6320 kg-m^2
Overall height	2.56 ft	0.78 m	2.56 ft	0.78 m	15.35 ft	4.68 m
Overall diameter	3.46 ft	1.06 m	3.46 ft	1.06 m	20.76 ft	6.33 m
Center of gravity above ground line	1.50 ft	0.46 m	1.50 ft	0.46 m	9.00 ft	2.74 m
Landing gear:						
Symmetric four-point (four legs 90°):						
Maximum radius	1.54 ft	0.47 m	1.54 ft	0.47 m	9.25 ft	2.82 m
Minimum radius	1.09 ft	0.33 m	1.09 ft	0.33 m	6.55 ft	2.00 m
Vertical stroke	0.35 ft	0.11 m	0.35 ft	0.11 m	2.10 ft	0.64 m
Shock-strut energy strap (each):						
Cross-sectional area	1.31×10^{-5} ft^2	1.22 μm^2	2.18×10^{-6} ft^2	0.202 μm^2	4.71×10^{-4} ft^2	0.0437 mm^2
Length	0.60 ft	0.18 m	0.60 ft	0.18 m	3.62 ft	1.10 m
Gear pads:						
Diameter	0.38 ft	0.12 m	0.38 ft	0.12 m	2.25 ft	0.69 m
Footprint area	0.12 ft	0.04 m	0.12 ft	0.04 m	4.32 ft	1.32 m

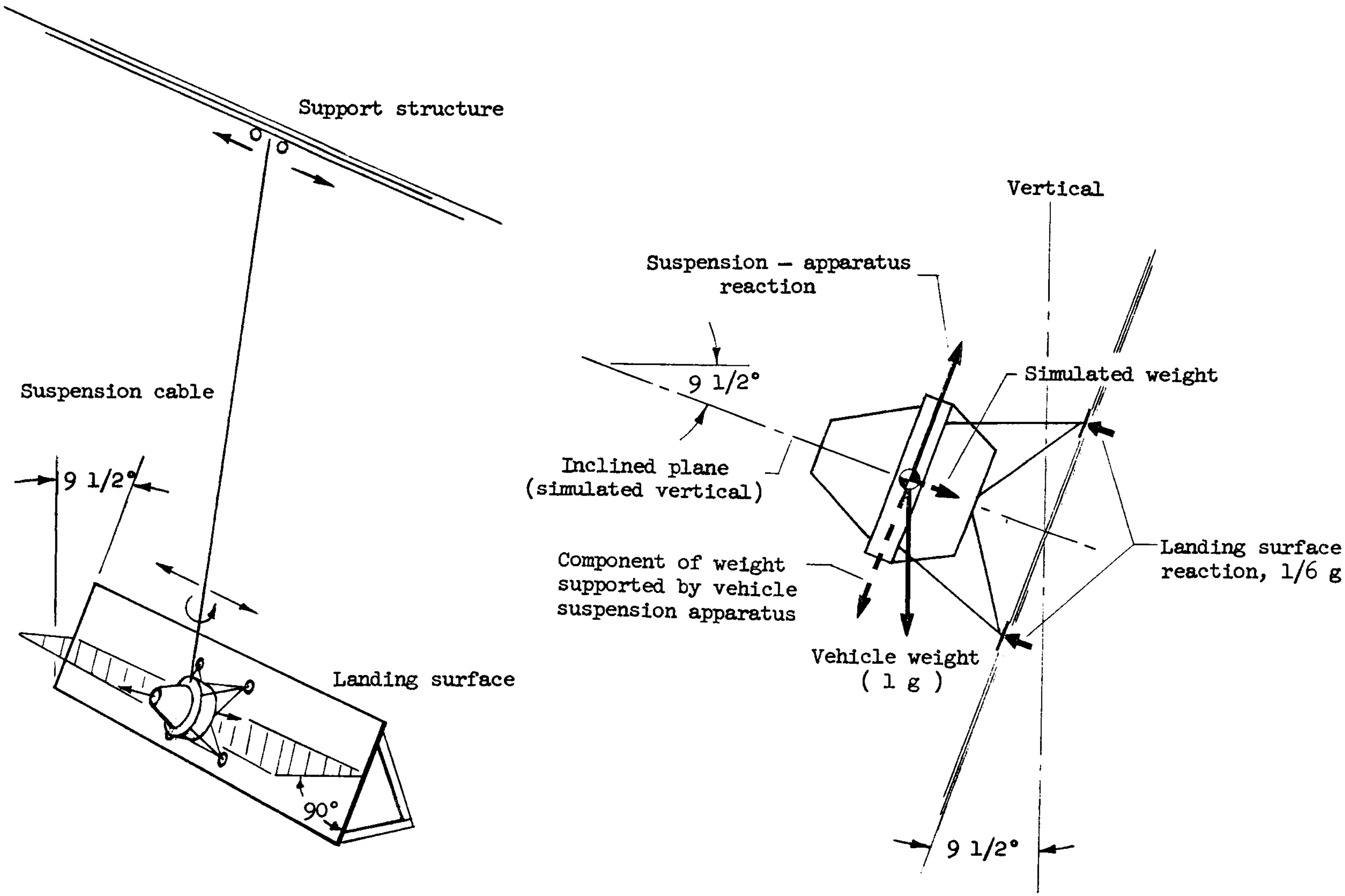


Figure 1.- Sketch illustrating principle of inclined-plane technique for simulation of lunar gravity.

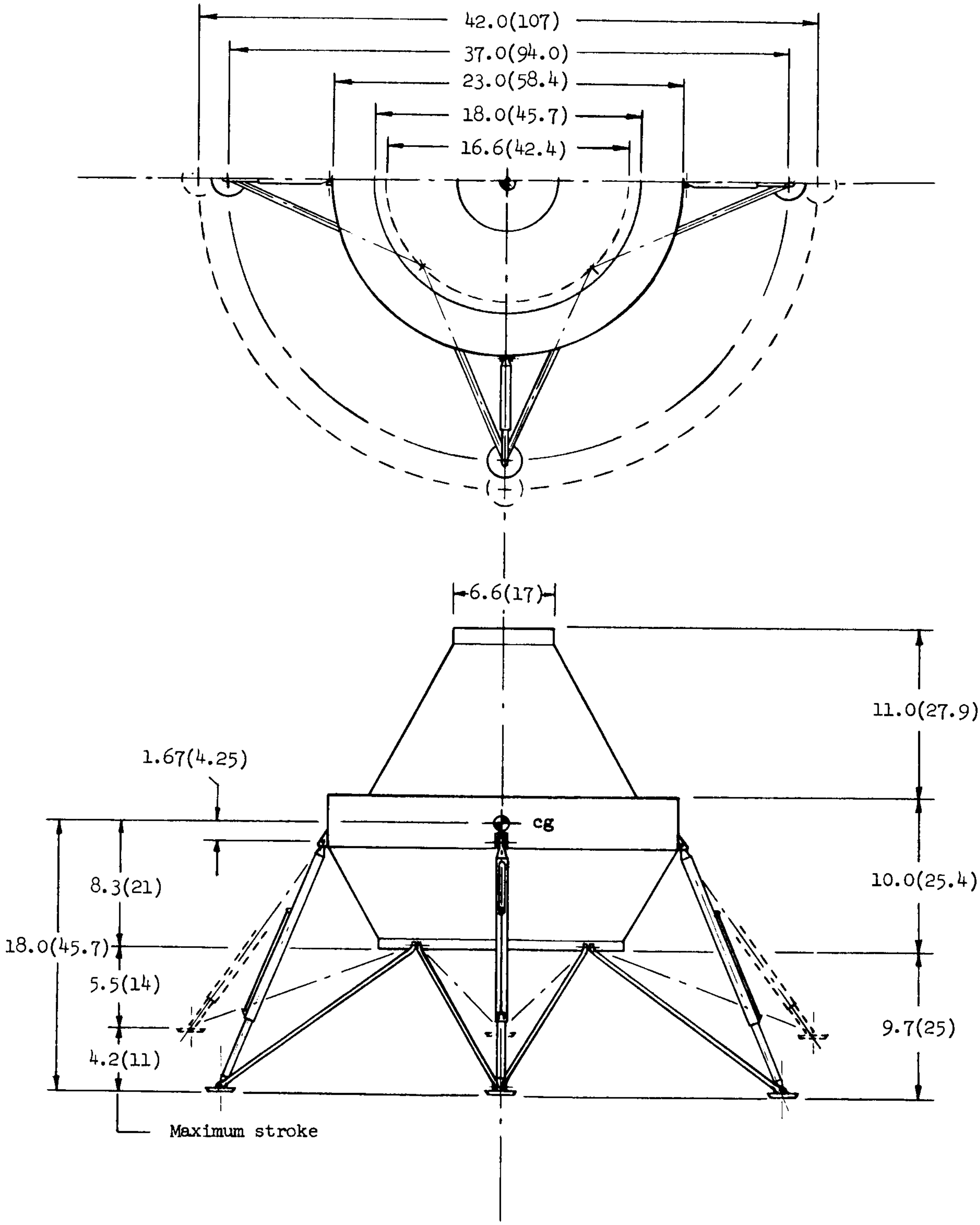


Figure 2.- General arrangement of 1/6-scale model. Initial dimensions are in inches; parenthetical dimensions are in centimeters.

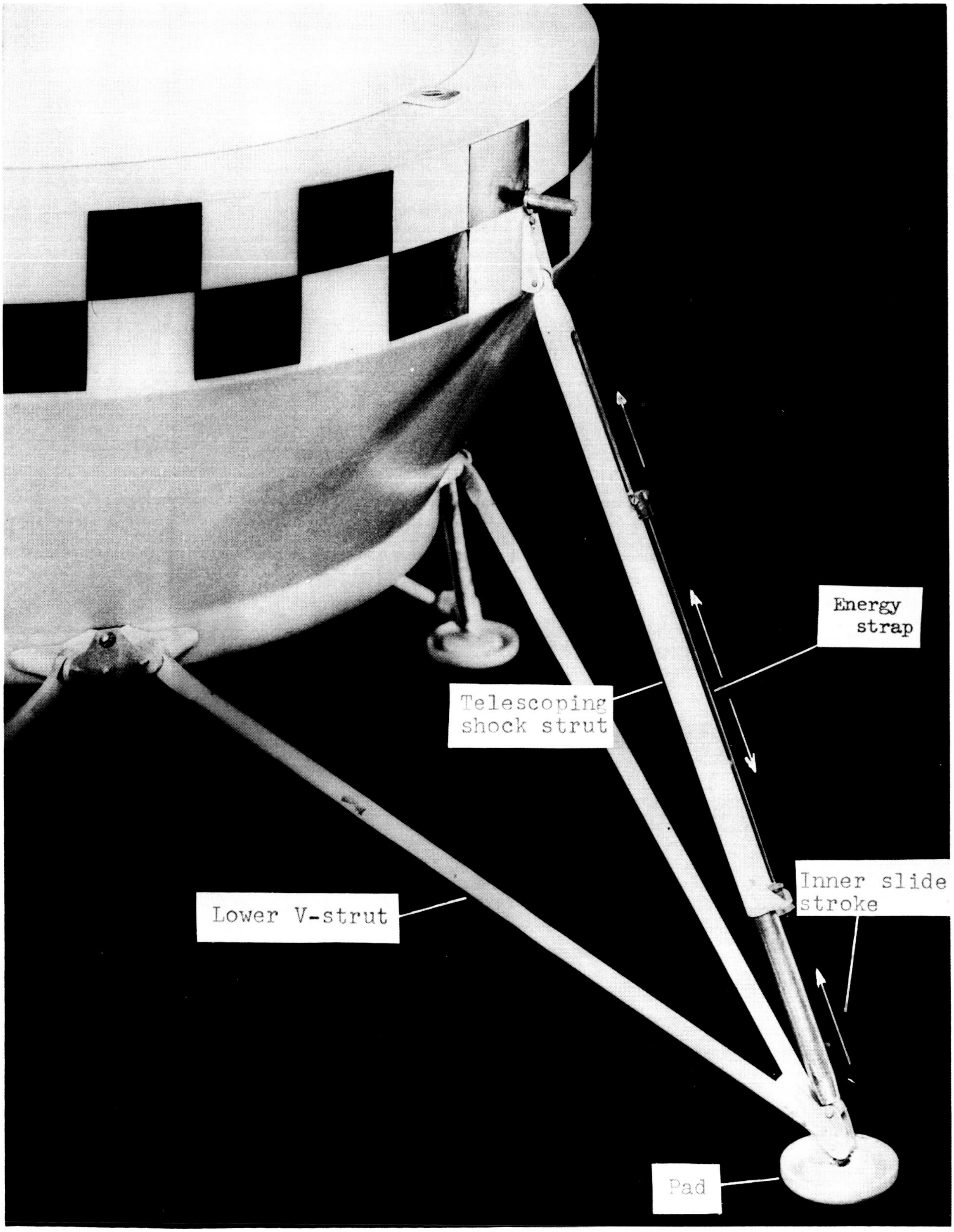


Figure 3.- Landing-gear assembly. L-65-1

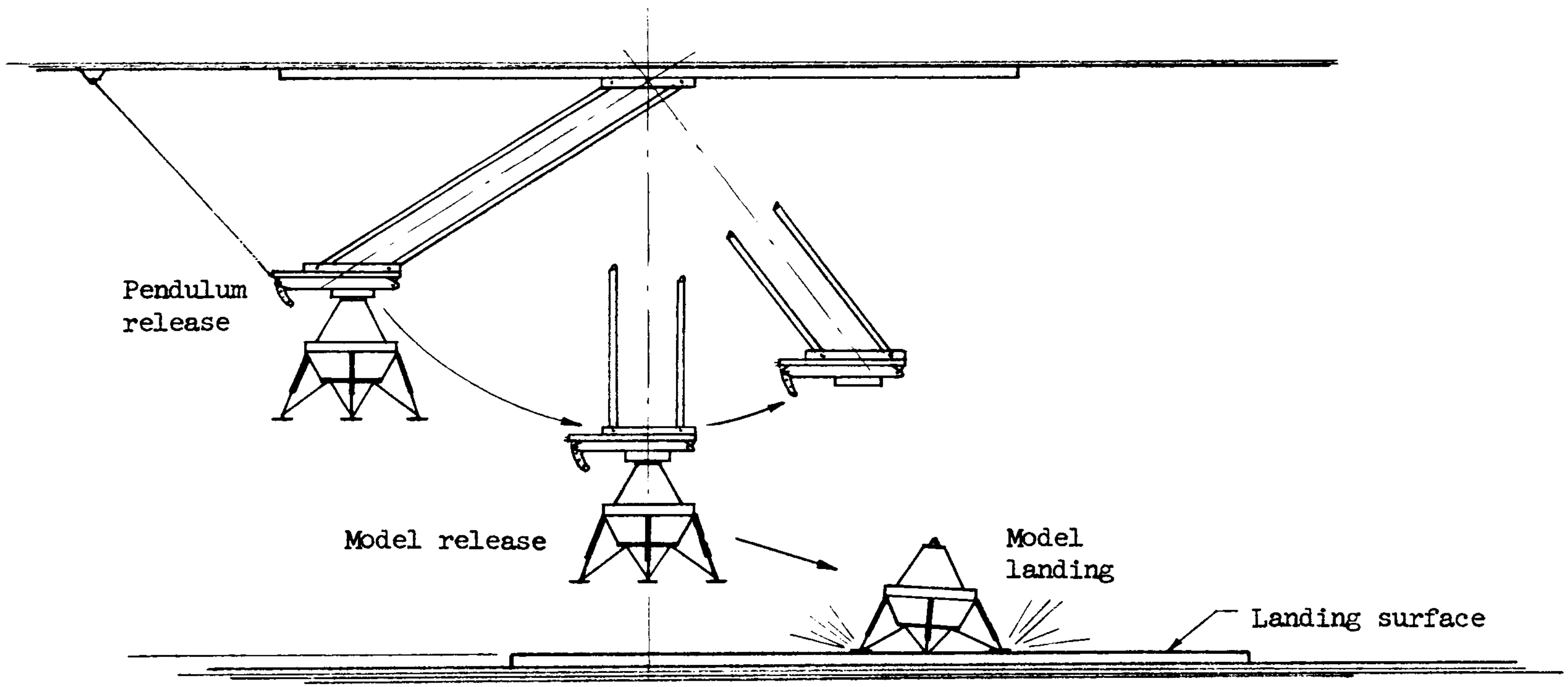


Figure 4.- Sketch showing earth-g (free body) apparatus.

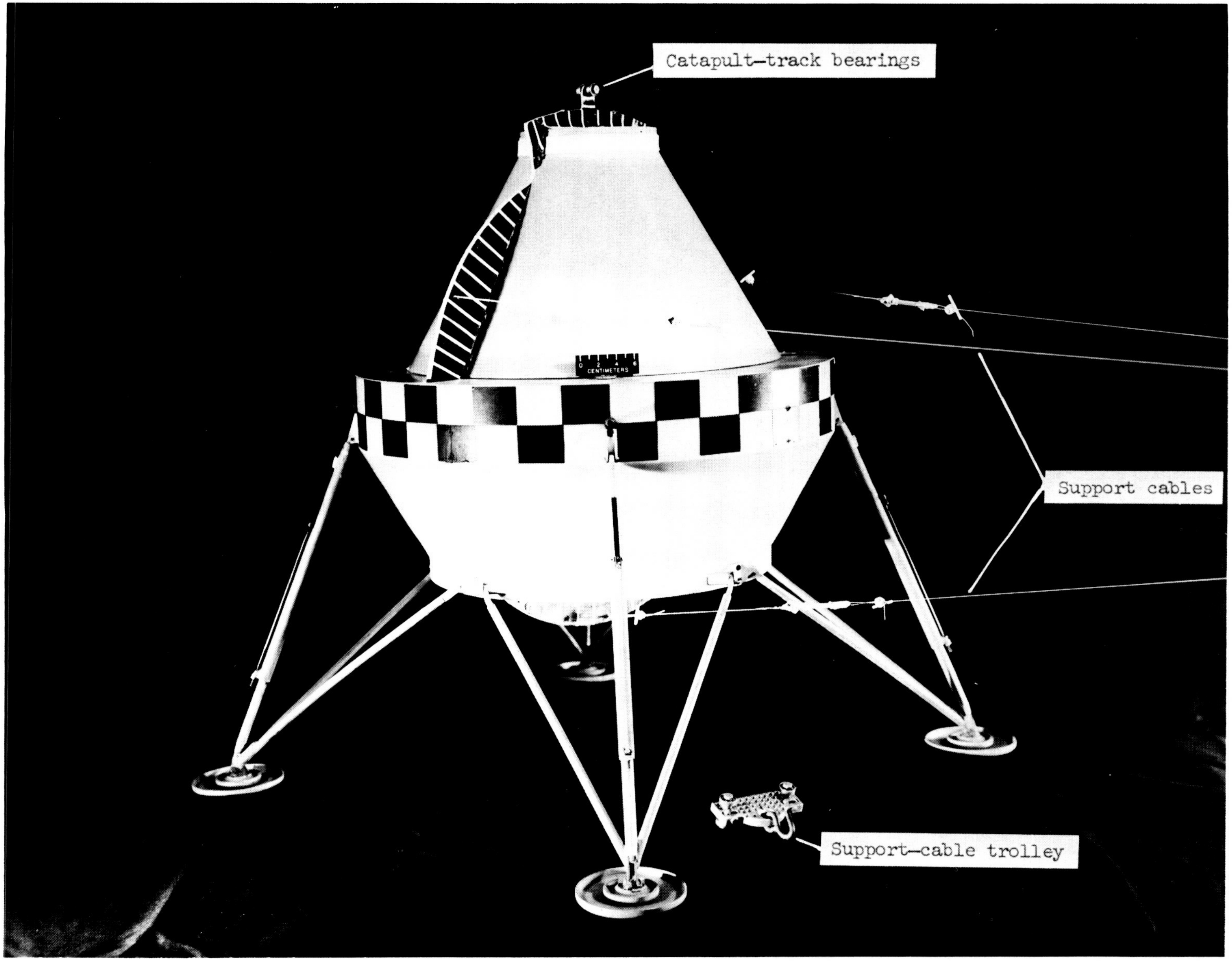


Figure 5.- Photograph of 1/6-scale model.

L-64-2353.1

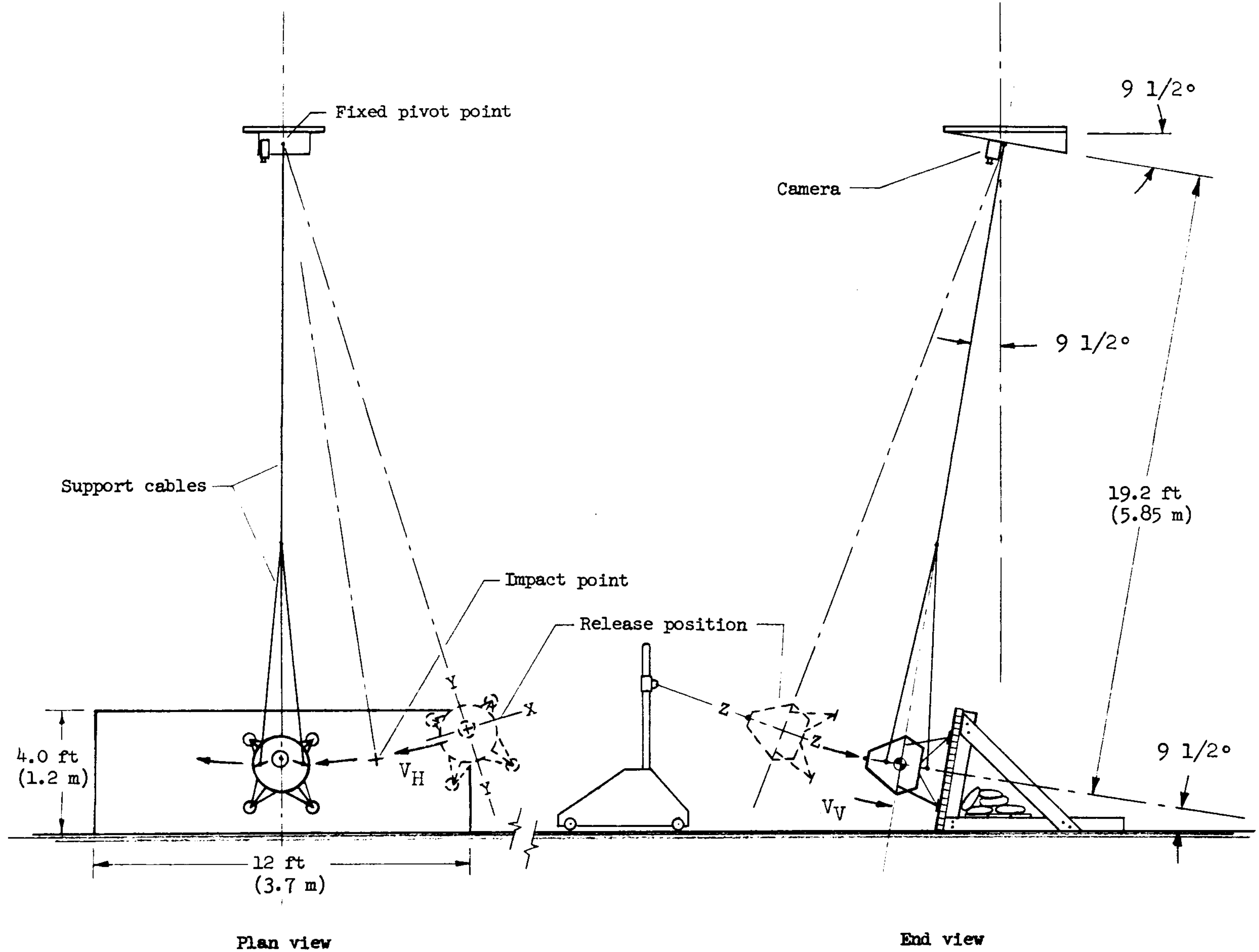


Figure 6.- Sketch showing 1/6 g pendulum apparatus.

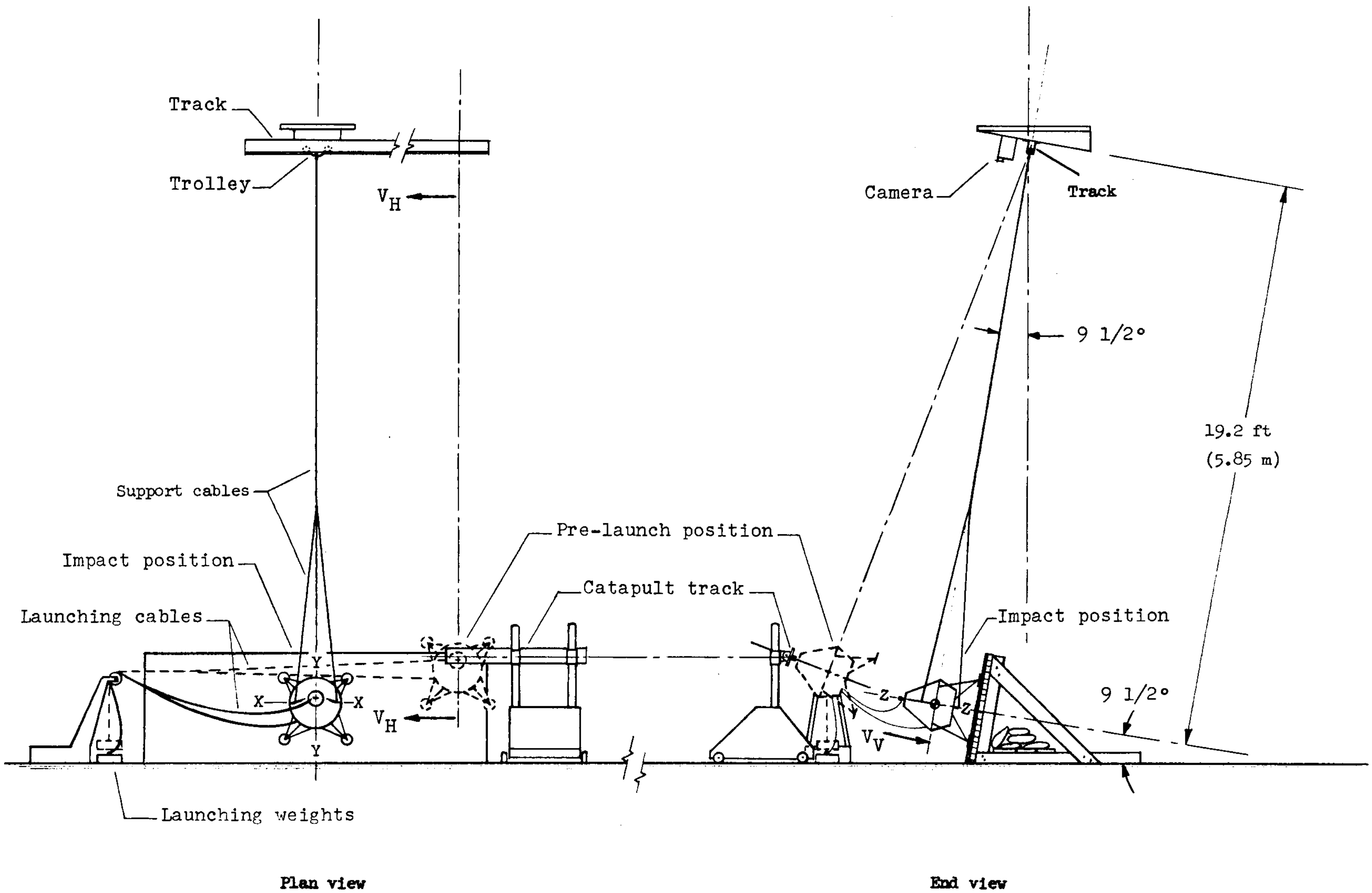


Figure 7.- Sketch showing 1/6 g pendulum-catapult apparatus.

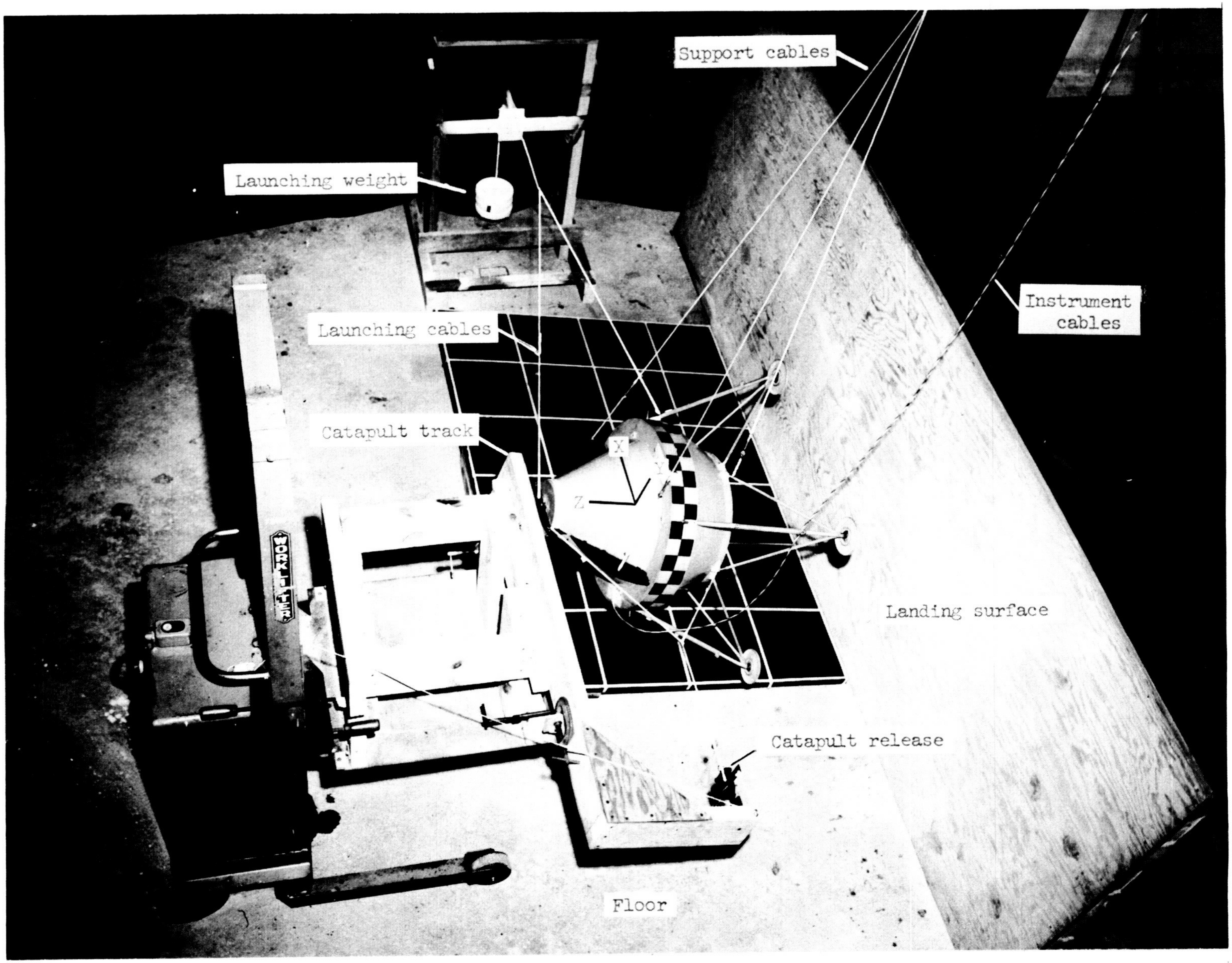
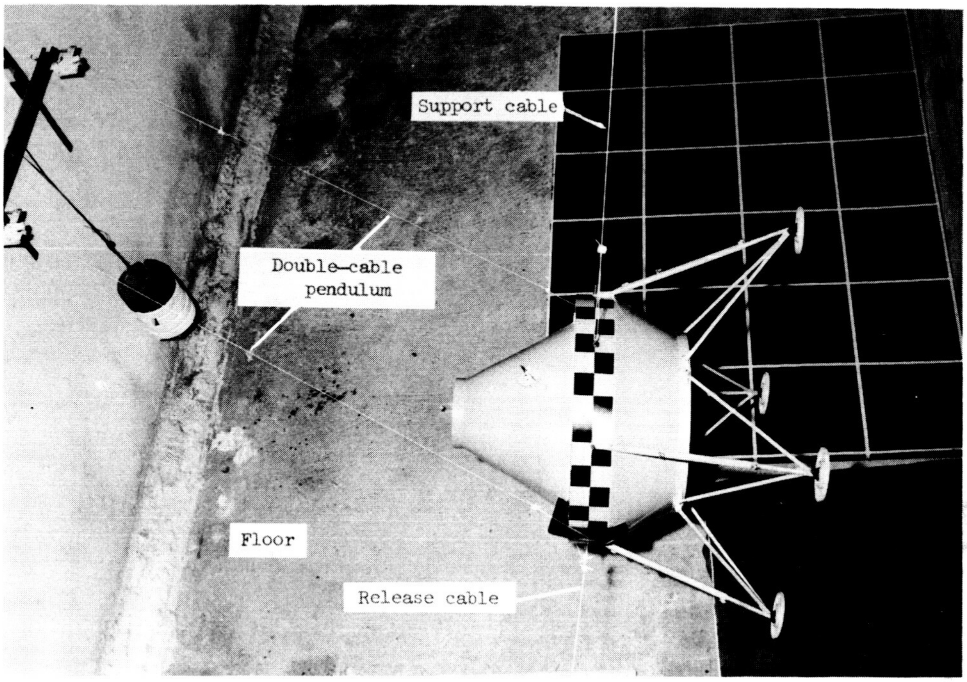
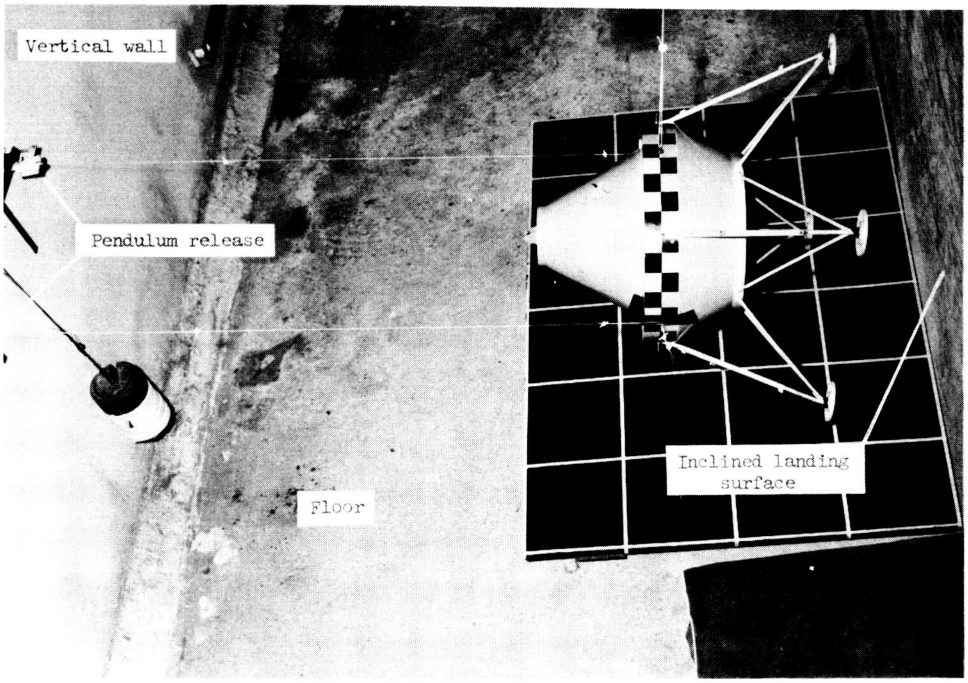


Figure 8.- Photograph of model on 1/6 g pendulum-catapult apparatus. L-64-631.1



(a) Pre-launch position.



(b) Launch position.

L-65-2

Figure 9.- Photograph of model on alternate 1/6 g pendulum-catapult apparatus.

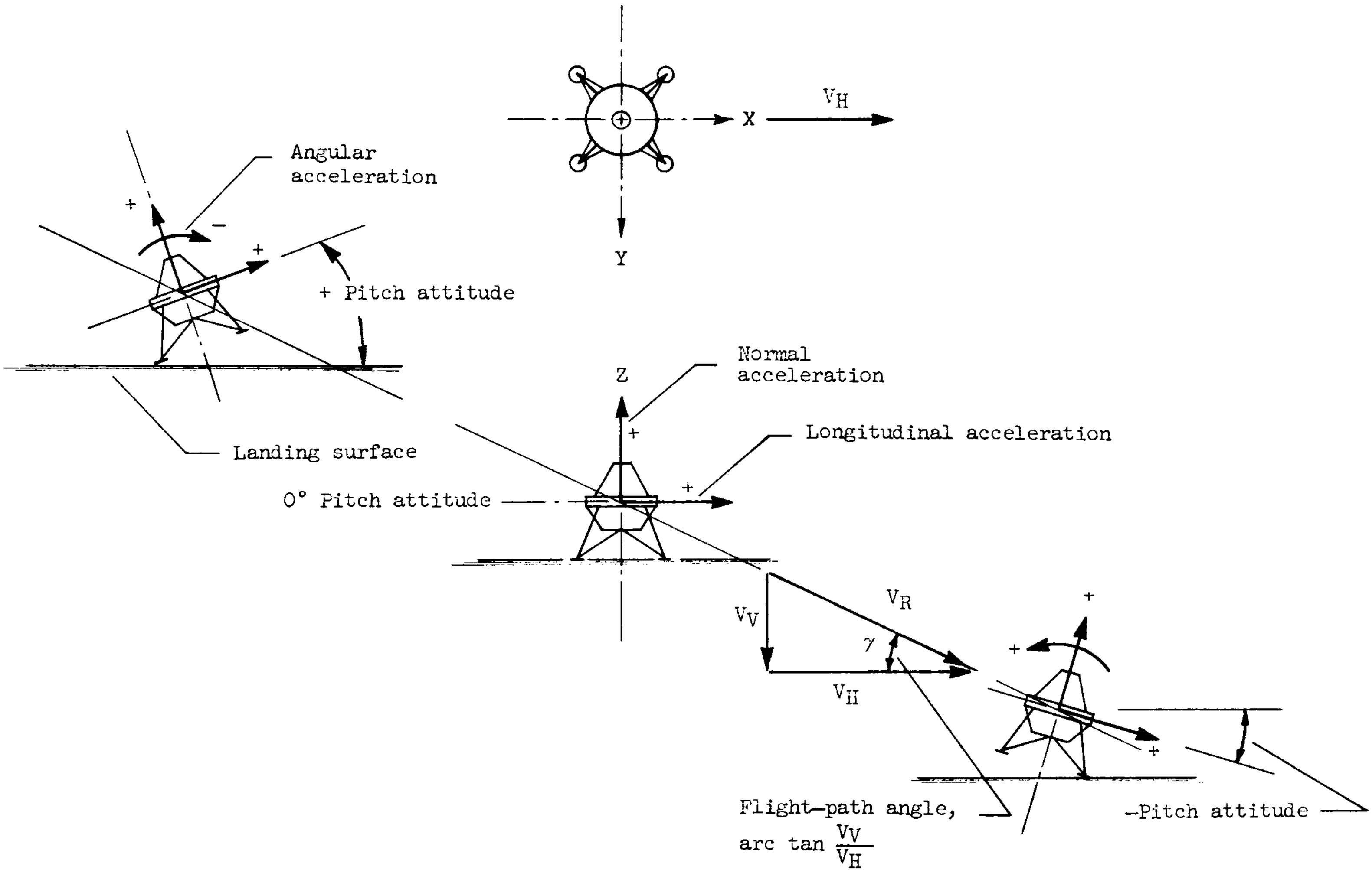
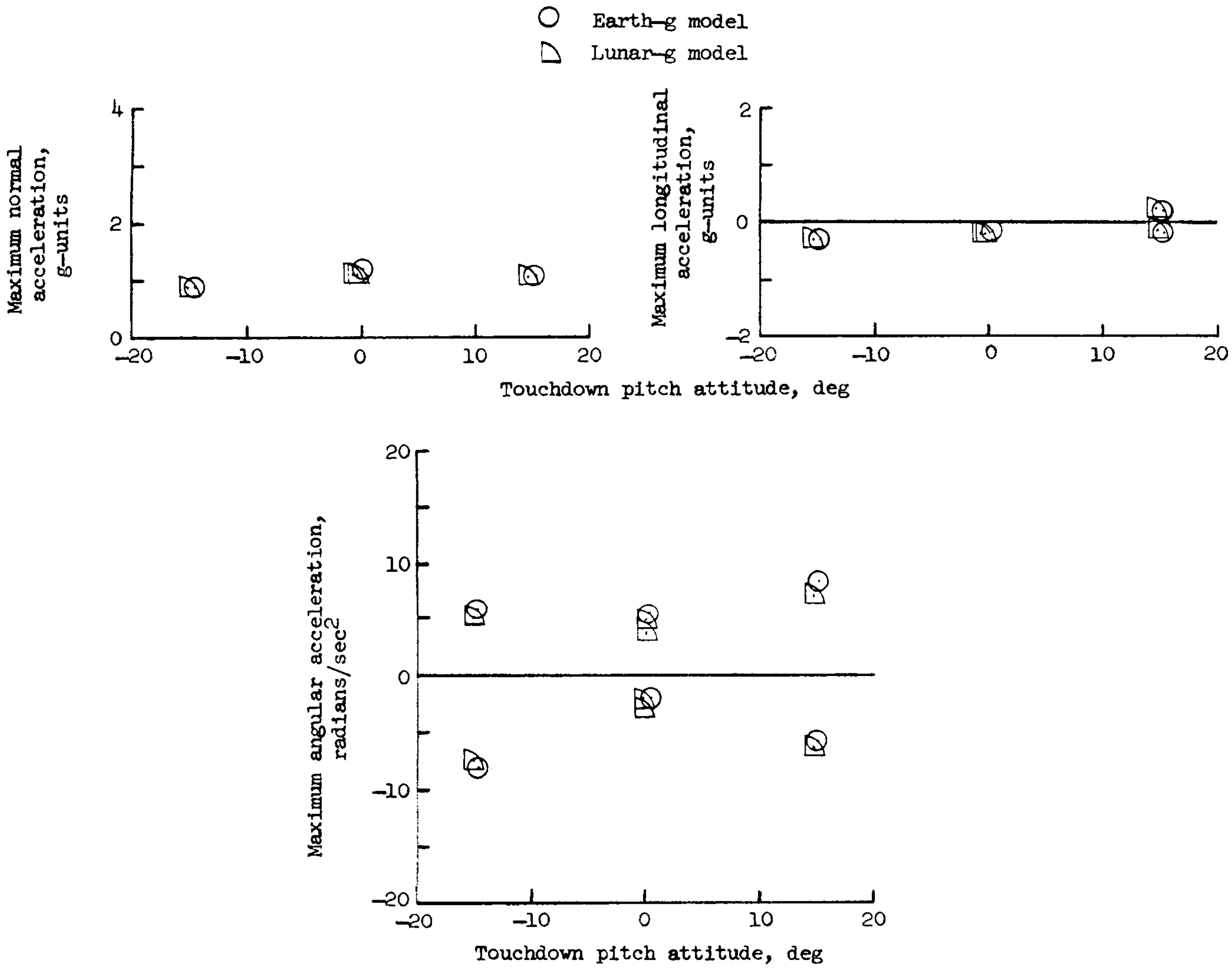
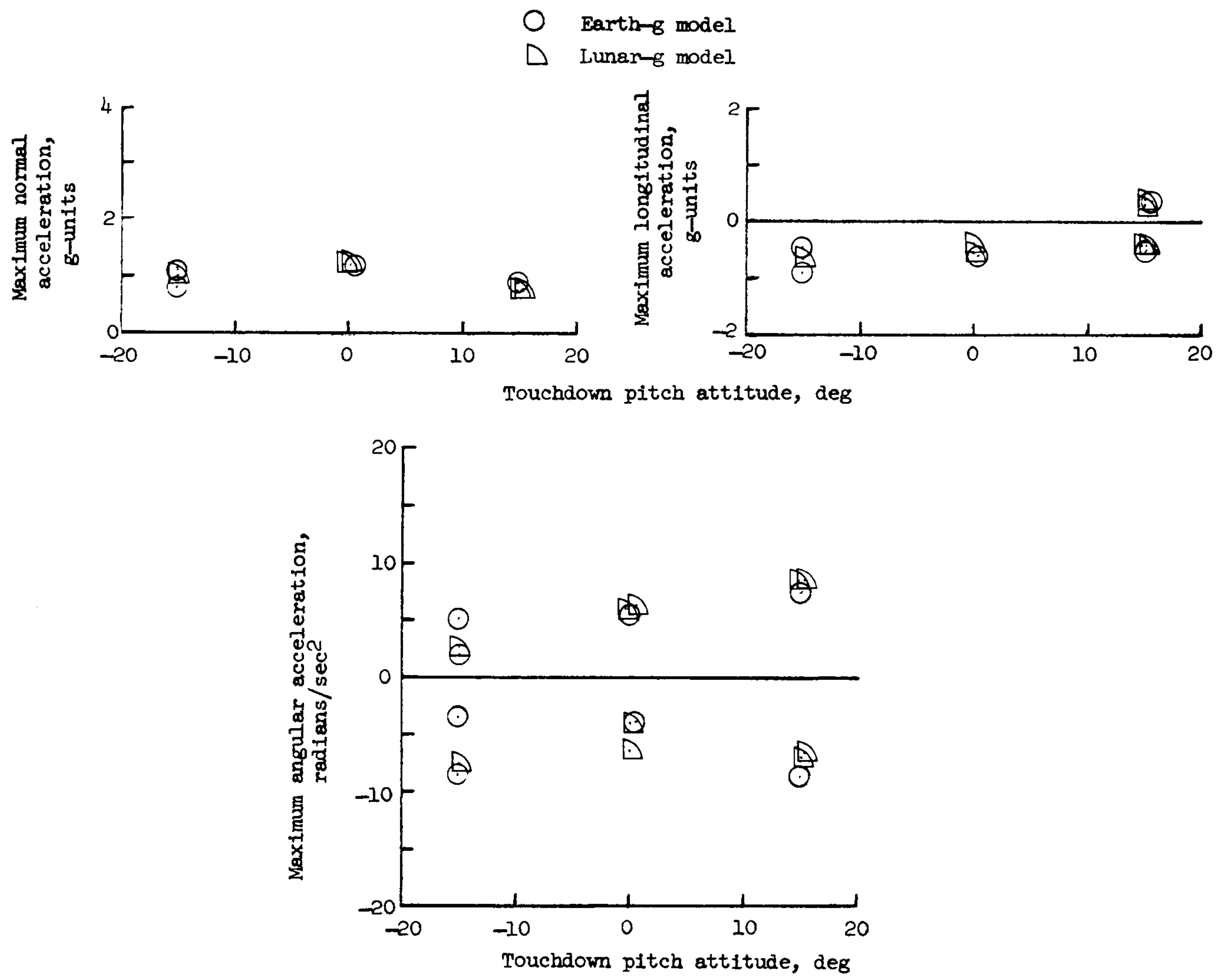


Figure 10.- Sketches identifying axes, accelerations, attitudes, speeds, and flight path.



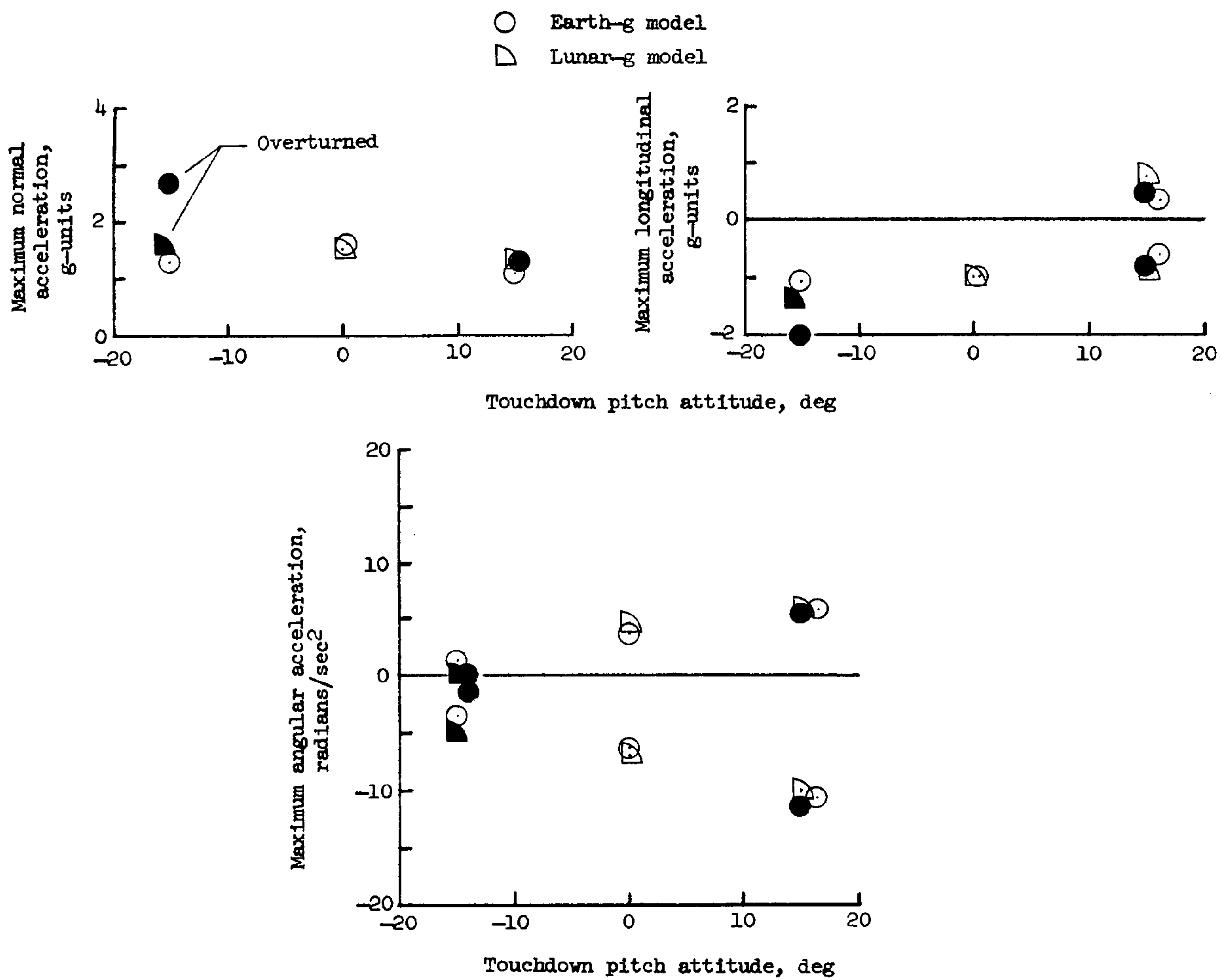
(a) Coefficient of friction, 0.1 to 0.2.

Figure 11.- Comparison of maximum impact accelerations obtained during landings on flat surface with earth-g and lunar-g model. V_V and V_H, 10 ft/sec (3.0 m/s). All values full scale.



(b) Coefficient of friction, 0.4 to 0.5.

Figure 11.- Continued.



(c) Coefficient of friction, 0.6 to 0.7.

Figure 11.- Concluded.

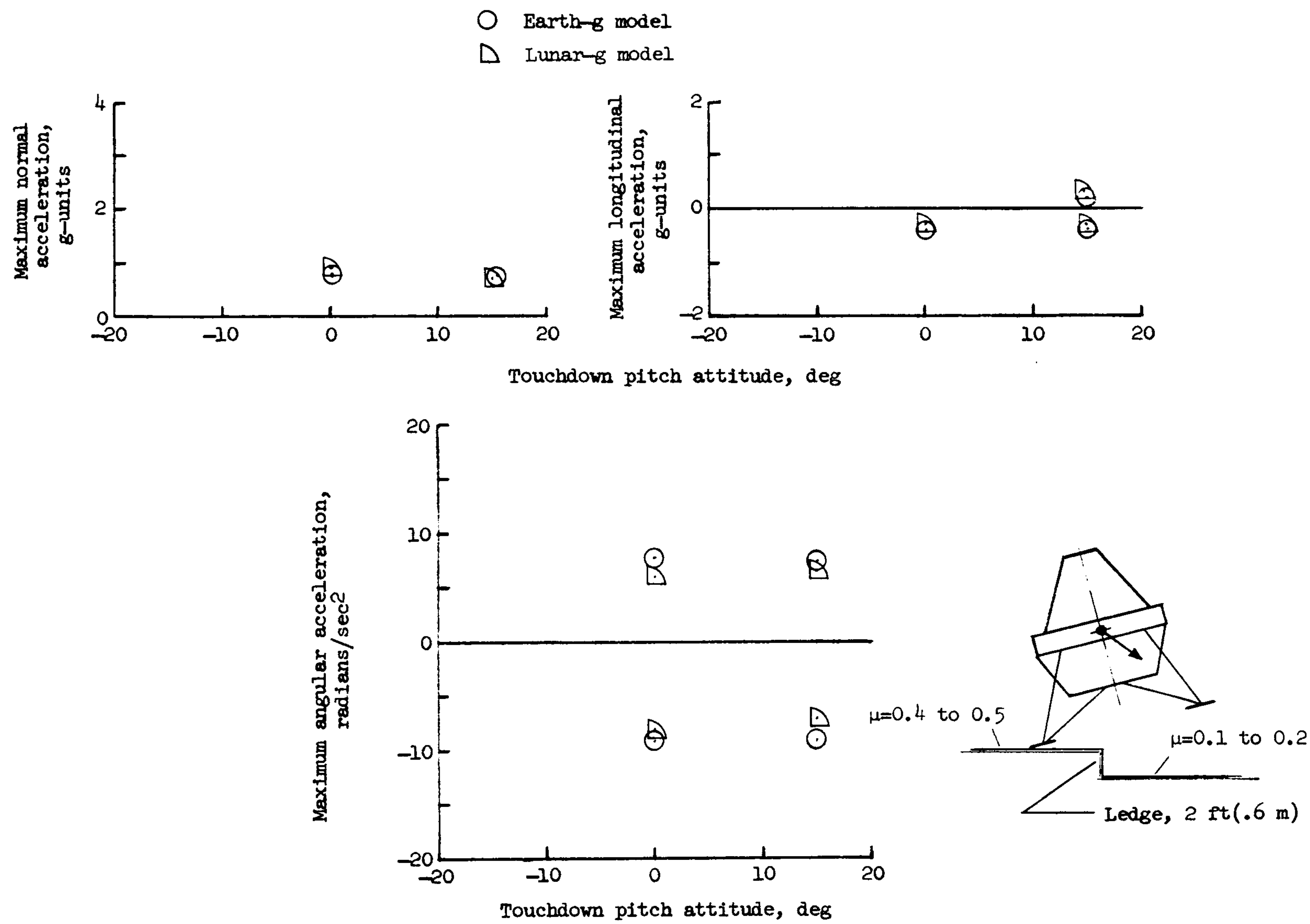
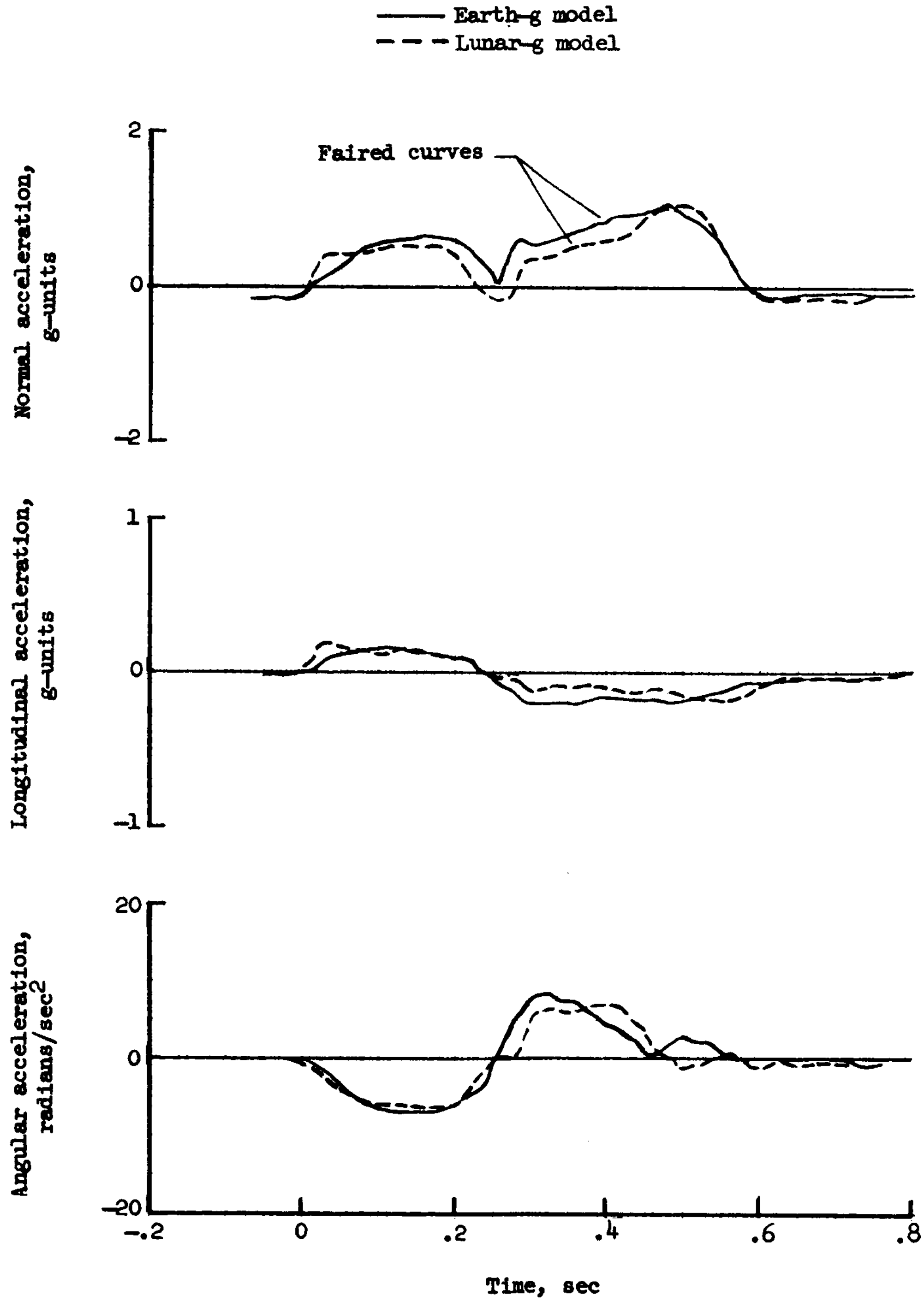
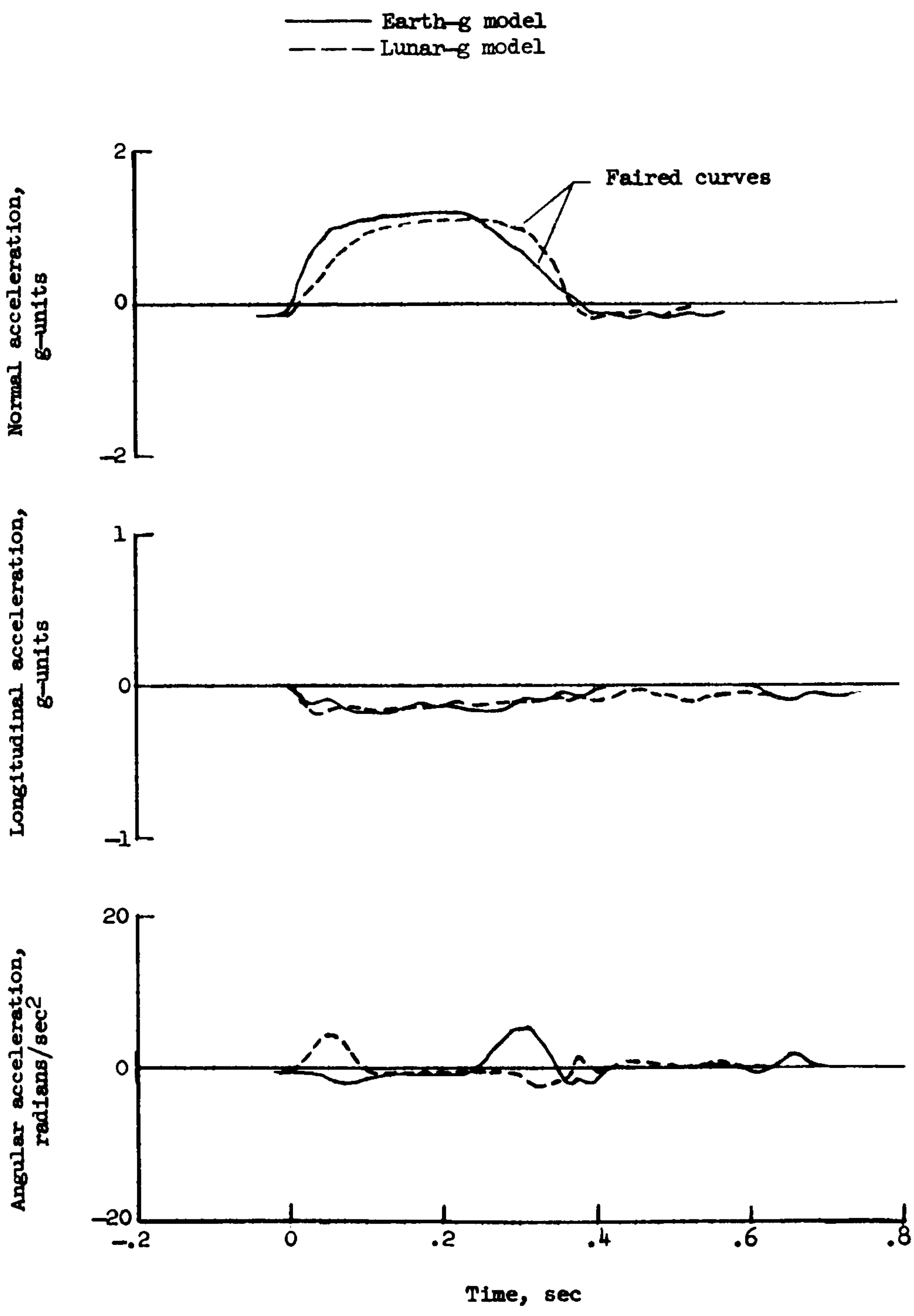


Figure 12.- Comparison of maximum impact accelerations obtained during landings on ledge surface with earth-g and lunar-g model. V_V and V_H, 10 ft/sec (3.0 m/s). All values full scale.



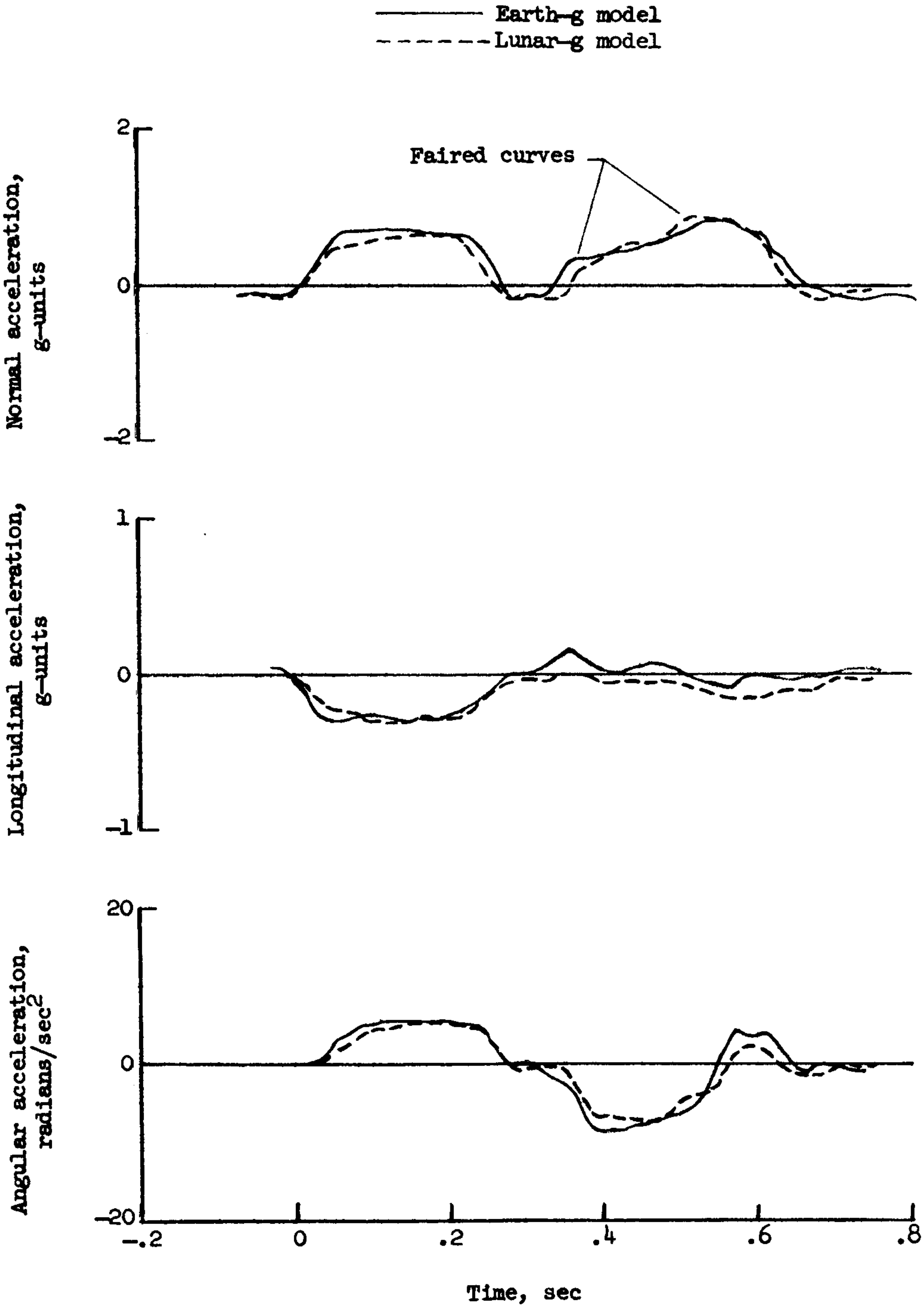
(a) Touchdown pitch attitude, 15°.

Figure 13.- Comparison of acceleration-time histories obtained during landings on flat surface with earth-g and lunar-g model. V_V and V_H, 10 ft/sec (3.0 m/s); μ, 0.1 to 0.2. All values full scale.



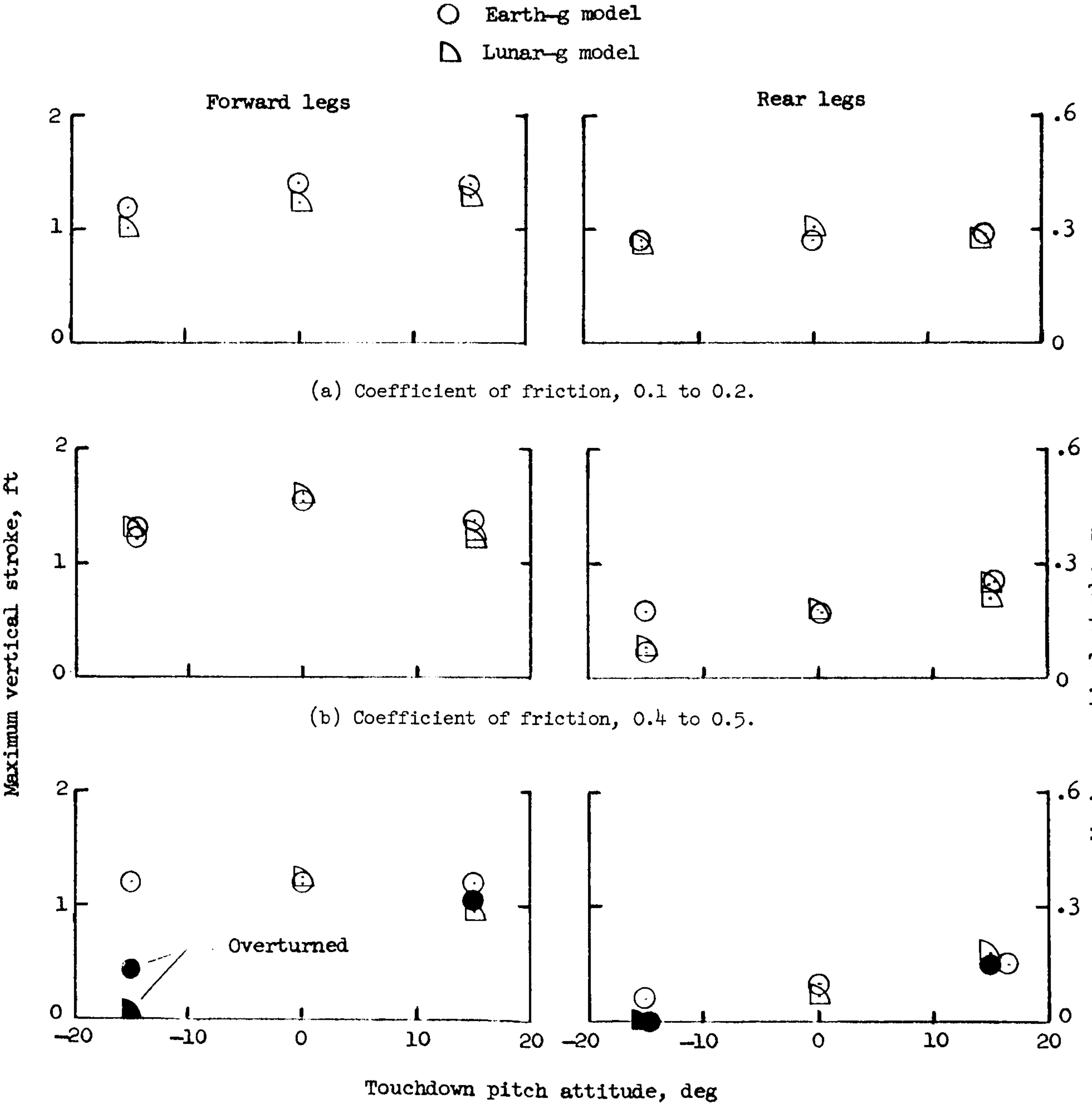
(b) Touchdown pitch attitude, 0°.

Figure 13.- Continued.



(c) Touchdown pitch attitude, -15°.

Figure 13.- Concluded.

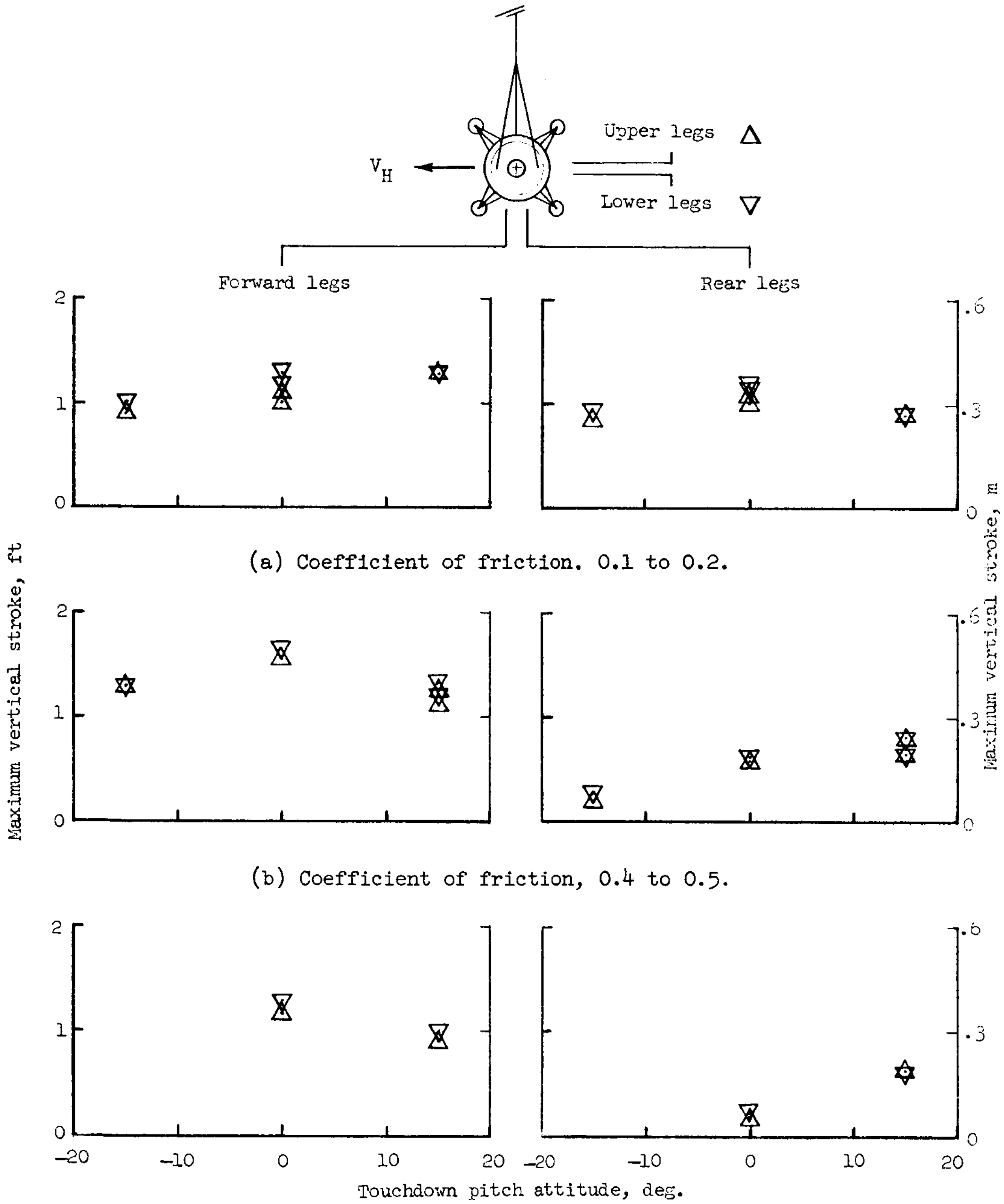


(a) Coefficient of friction, 0.1 to 0.2.

(b) Coefficient of friction, 0.4 to 0.5.

(c) Coefficient of friction, 0.6 to 0.7.

Figure 14.- Comparison of maximum landing-gear stroke obtained during landings on flat surface with earth-g and lunar-g model. V_V and V_H, 10 ft/sec (3.0 m/s). All values full scale.



(a) Coefficient of friction, 0.1 to 0.2.

(b) Coefficient of friction, 0.4 to 0.5.

(c) Coefficient of friction, 0.6 to 0.7.

Figure 15.- Comparison of maximum stroke of upper and lower gear legs during landings with lunar-g model. V_V and V_H, 10 ft/sec (3.0 m/s). All values full scale.

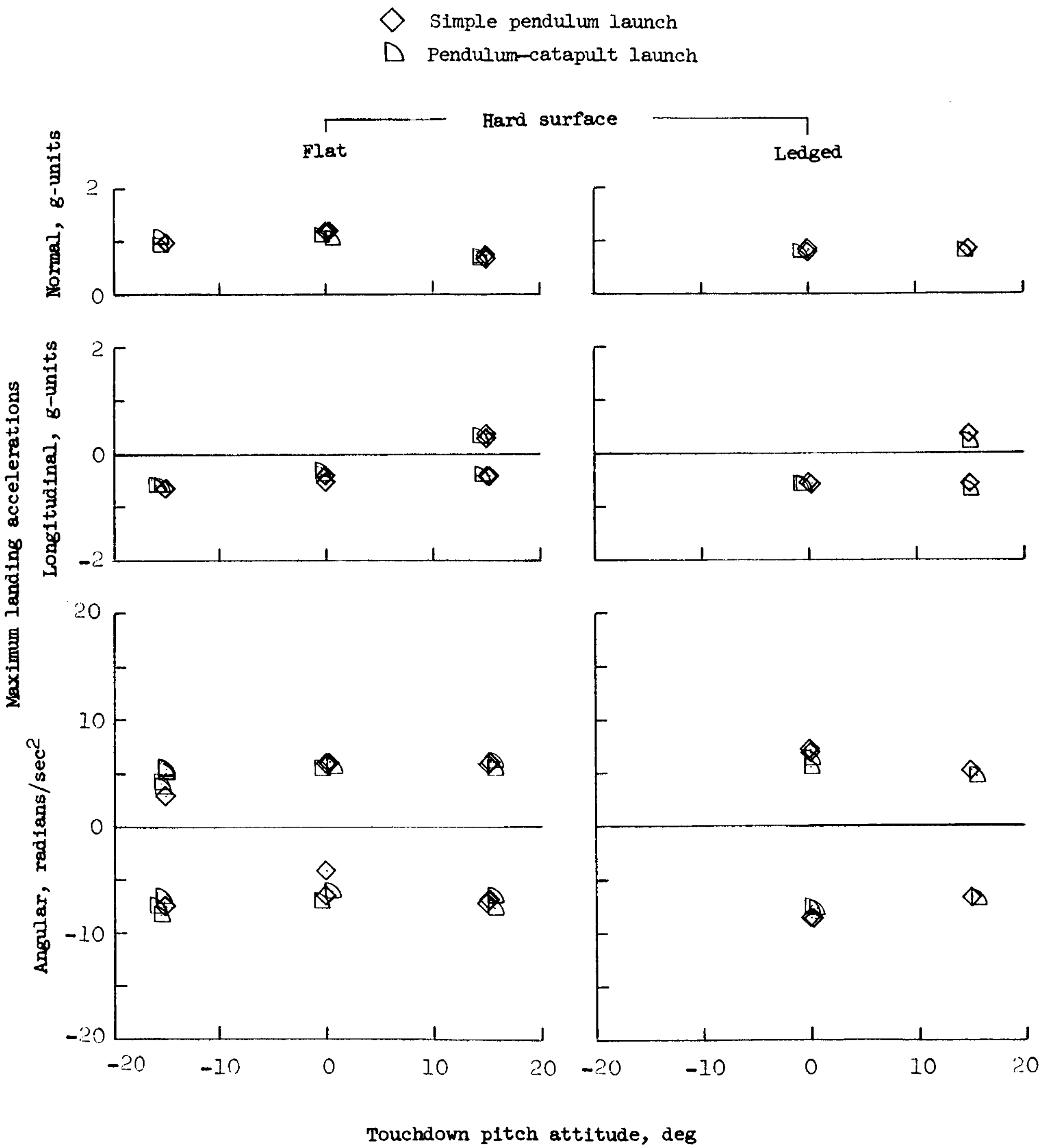


Figure 16.- Comparison of maximum impact accelerations obtained during landings with lunar-g model with two launch techniques. V_V and V_H, 10 ft/sec (3.0 m/s). All values full scale.

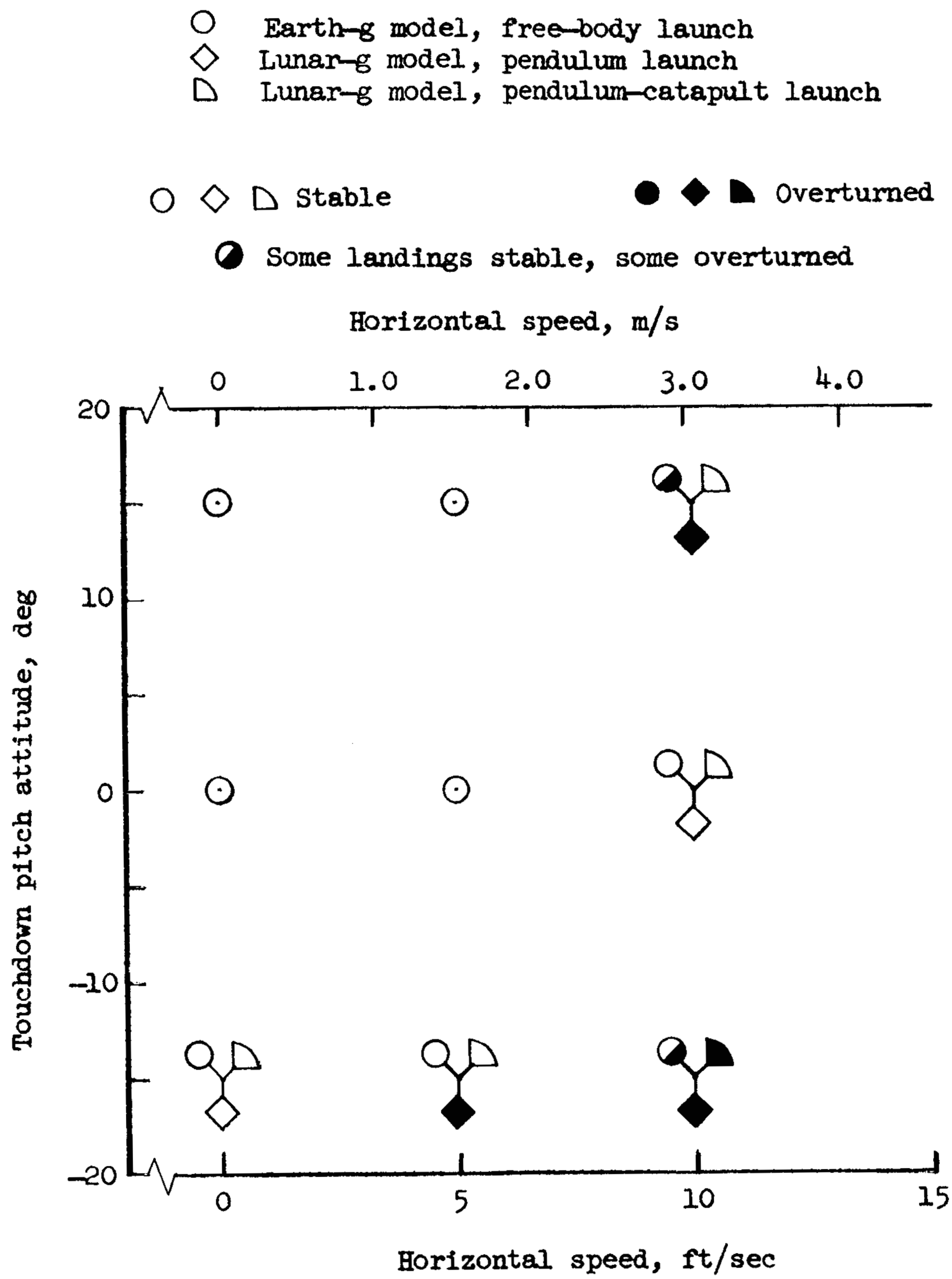


Figure 17.- Comparison of overturn stability during landings using the free-body and inclined-plane test techniques. Vertical speed, 10 ft/sec (3.0 m/s); coefficient of friction, 0.6 to 0.7.

A motion-picture film supplement L-856 is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm, 4 min, color, silent) shows comparative test landings of the 1/6-scale model using the free-body earth-gravity technique and the inclined-plane lunar-gravity simulation technique.

Requests for the film should be addressed to:

Chief, Photographic Division
NASA Langley Research Center
Langley Station
Hampton, Va. 23365

C U T

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